Modeling of Aqueous Film Forming Foam (AFFF) Fire Extinguishment Performance

Brian Y. Lattimer, Javier Trelles, Chris Hanauska, and Joe Scheffey

410.737.8677

www.haifire.com

HUGHES ASSOCIATES, INC.
FIRE SCIENCE & ENGINEERING

Jim Milke
Univ. of Maryland
Dept. of Fire Protection Eng.

Fred Williams
Naval Research Lab

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Topics

- Background
- Previous work
- Modeling approach
- Equations of motion
  - Source terms and some boundary conditions
- Numerical methods
- 1-D model results
- Next steps in modeling
- Experimental
- Timeline
- Publications

Background

- Alternative agents being developed
  - Environmentally friendly
- Performance evaluation impeding progress
  - Full-scale test required to determine performance
- Lack of understanding of foam extinguishment mechanism
  - Current small-scale tests not measuring all important parameters
  - Performance a function of multiple parameters

Background

- Goals of study
  - Accelerate the evaluation process of foam
    - Develop model
      - Predict full-scale performance of a foam
    - Use / develop small-scale tests
      - Measure performance of specific aspects of foam
        - Drainage, evaporation, spreading characteristics
      - Model input data
  - Near term goal of predicting MIL-SPEC test
    - 28 and 50 ft^2 MOGAS pool fires

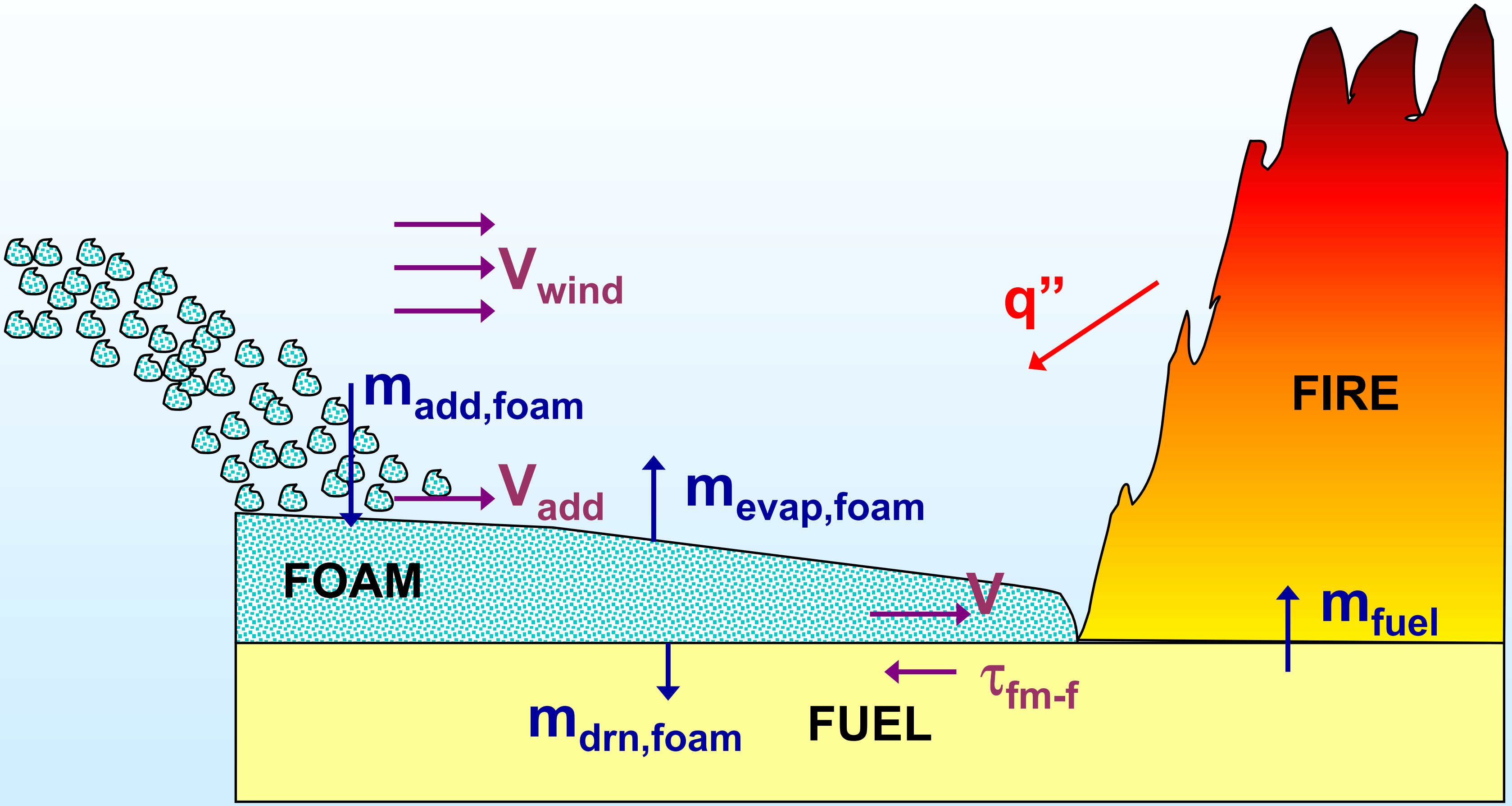
Previous Work

- Swedish National Laboratory and Research Institute (SP)
  - Small-scale tests
    - Drainage and evaporation rates
    - Viscosity of foam
  - Large-scale foam spread tests
    - With and without fire
  - Nozzle characterization
    - Some velocity and mass distribution
  - Modeling
    - Simplified 1-D cases
    - Meshing of 1-D cases for 2-D case

Previous Work

- SP (continued)
  - Conclusion
    - Modeling approach not capable of predicting very large scale tests with hose line application
- Several studies on modeling foam drainage and evaporation
  - Perssons et al. (1992, 1996, 1997), Magrabi, et al. (1997)
- Ablation model for Hi-Ex foams
  - Boyd and Di Marzo (1998)
- Rheology of foam
  - Gardiner et al. (1998)

Modeling Approach



Modeling Approach

- Field model
  - Model foam spreading
    - Gravity driven flow
      - Hydraulics / hydrology of river flows
  - Divide space above fuel into a single layer of cells
    - Cell thickness varies
    - Average properties over height of foam
  - Source terms from small-scale test data
    - Solution drainage
    - Solution evaporation
    - Foam addition from nozzle
    - Momentum from nozzle spray
    - Shear force between foam and fuel

Modeling Approach

- Thermal modeling
  - Radiation from fire to foam
    - Emissive power of fire and configuration factors
  - Evaporation of foam dependent on predicted incident flux onto foam
  - No predictions of foam temperatures in initial versions
    - Small-scale testing shows no heat transfer to fuel until foam less than 25 mm (1.0 in.) thick

Equations of Motion

Conservation of Mass

$$\frac{\partial(\rho h)}{\partial t} + \frac{\partial(\rho uh)}{\partial x} + \frac{\partial(\rho vh)}{\partial y} = \underbrace{\dot{m}''_{add}}_{\text{Foam Added}} - \overbrace{\dot{m}''_{dr}}^{\text{Foam Drained}} - \underbrace{\dot{m}''_{evap}}_{\text{Foam Evaporated}} \equiv \dot{m}''$$

Conservation of Momentum

$$\frac{\partial(\rho uh)}{\partial t} + \frac{\partial}{\partial x}\left(\rho u^2 h + \underbrace{\frac{1}{2}\rho g h^2}_{\text{Gravity Force}}\right) + \frac{\partial(\rho uvh)}{\partial y} = \underbrace{\rho f_x h}_{\text{Other Body Forces}}$$

$$\frac{\partial(\rho vh)}{\partial t} + \frac{\partial(\rho uvh)}{\partial x} + \frac{\partial}{\partial y}\left(\rho v^2 h + \frac{1}{2}\rho g h^2\right) = \rho f_y h$$

Equations of Motion

- Other body forces
  - Shear between foam and fuel
  - Shear from external air currents
    - Wind
    - Air entrainment into fire
  - Momentum from foam application
  - Surface tension
- Various boundary conditions
  - Effects of obstructions

Numerical Methods

- Hyperbolic set of partial differential equations
  - Unsteady shallow water equation
  - Review Zappou and Roberts (2003?) of different numerical schemes
    - Godnov-type schemes better than finite difference
      - Approximate Riemann solvers
    - 2nd order accurate approximate Riemann solvers
      - High resolution, robust, efficient
      - Optimal for application
  - Weighted Average Flux (WAF) routine implemented
    - 2nd order accurate
    - Robust and efficient

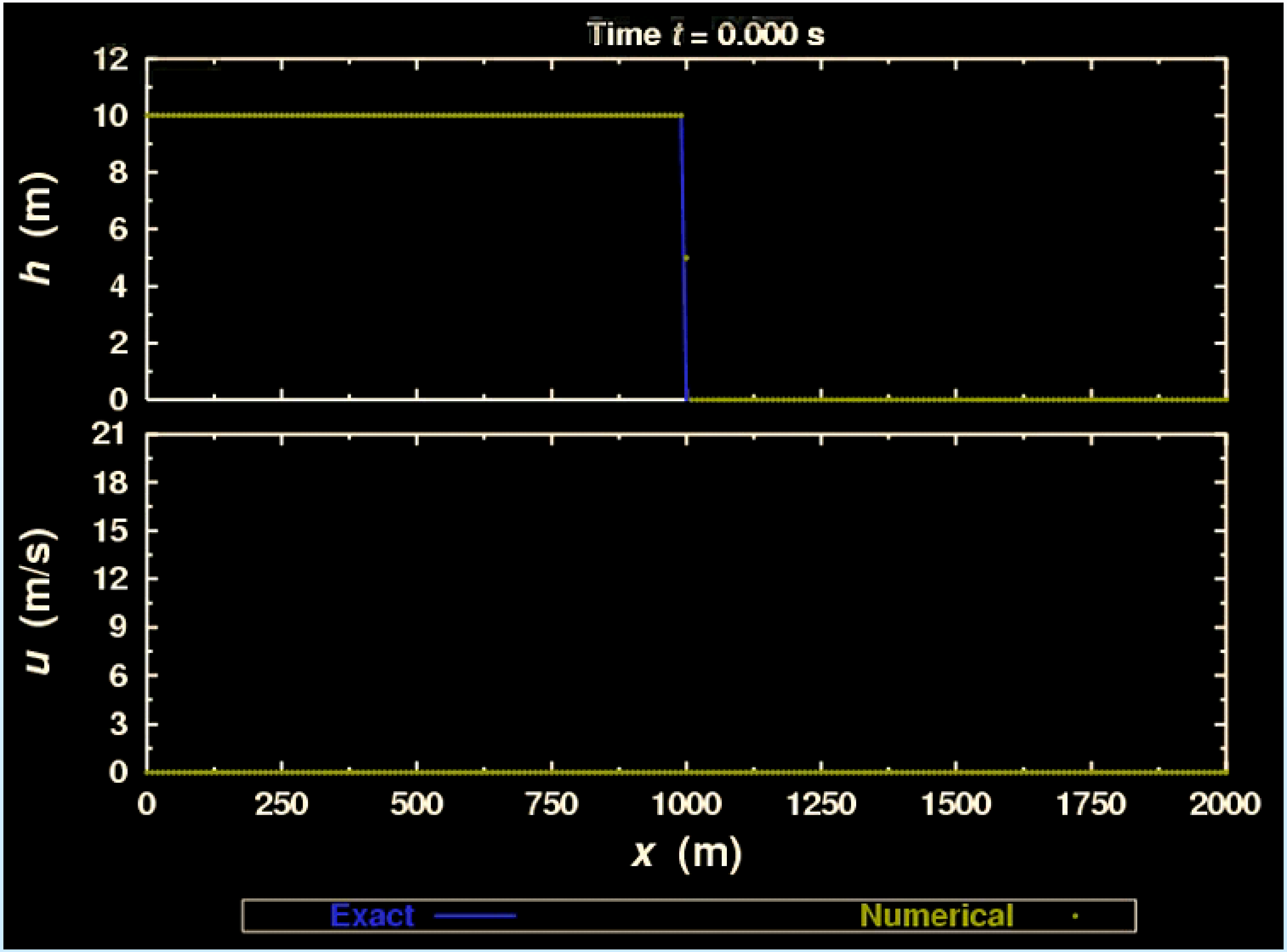
1-D Shallow Water Equation

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} = 0.$$

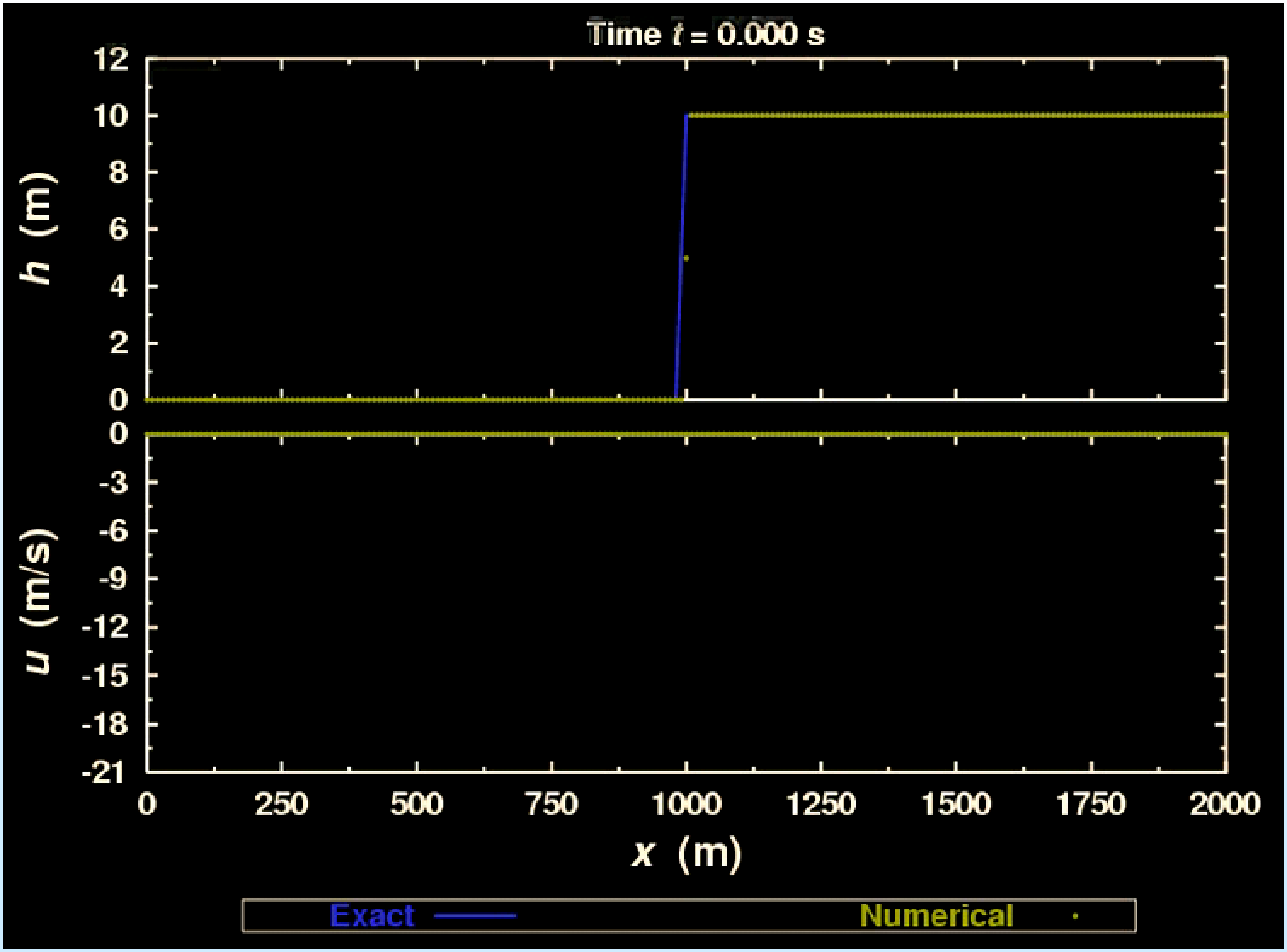
$$\frac{\partial (uh)}{\partial t} + \frac{\partial}{\partial x}\left(u^2 h + \frac{1}{2} g\, h^2 \right) = 0$$

- Assumptions
  - No source terms
  - Constant density
- Verification
  - Compared against exact solutions to Riemann problem

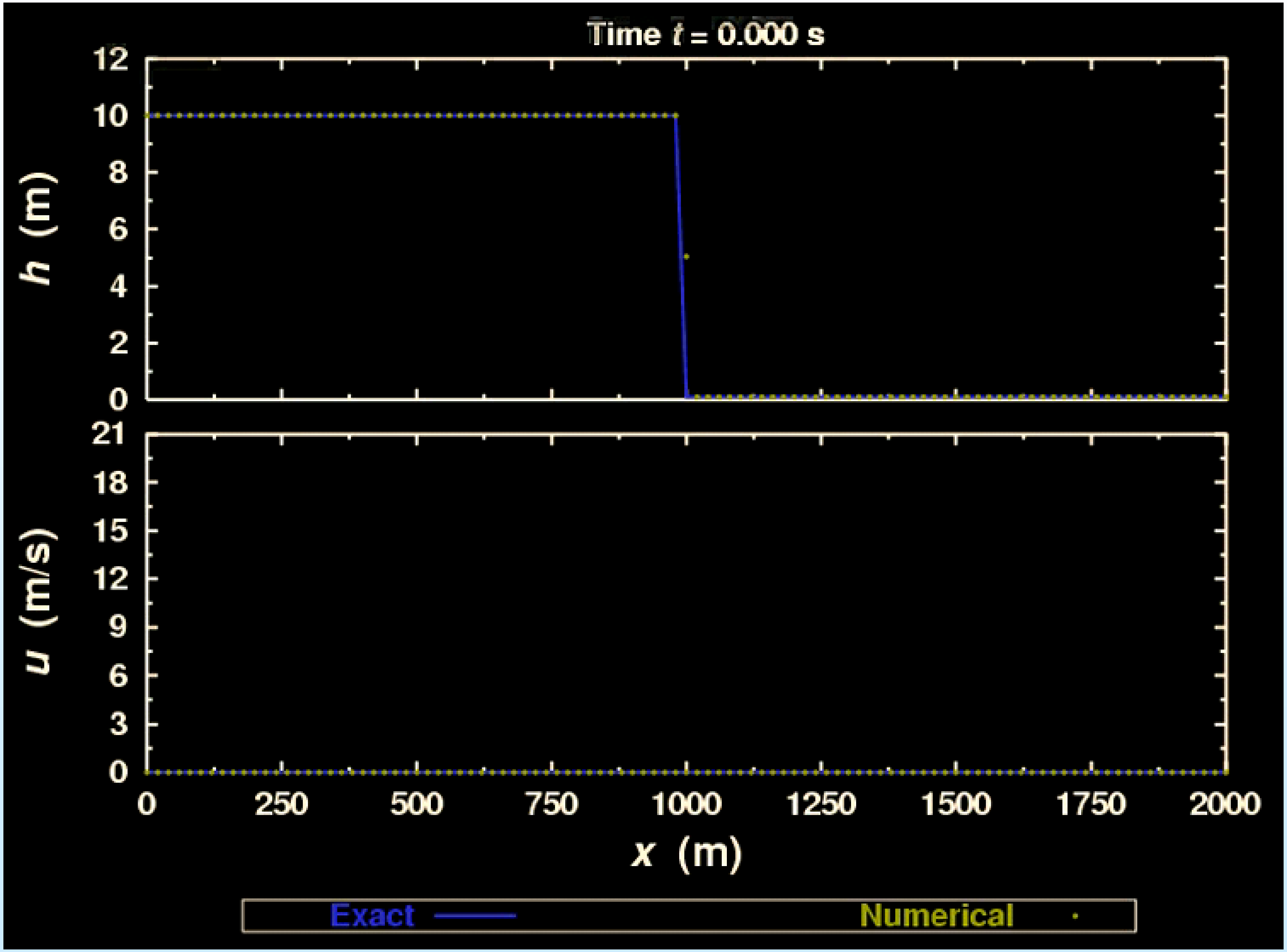
Dry Bed Problem



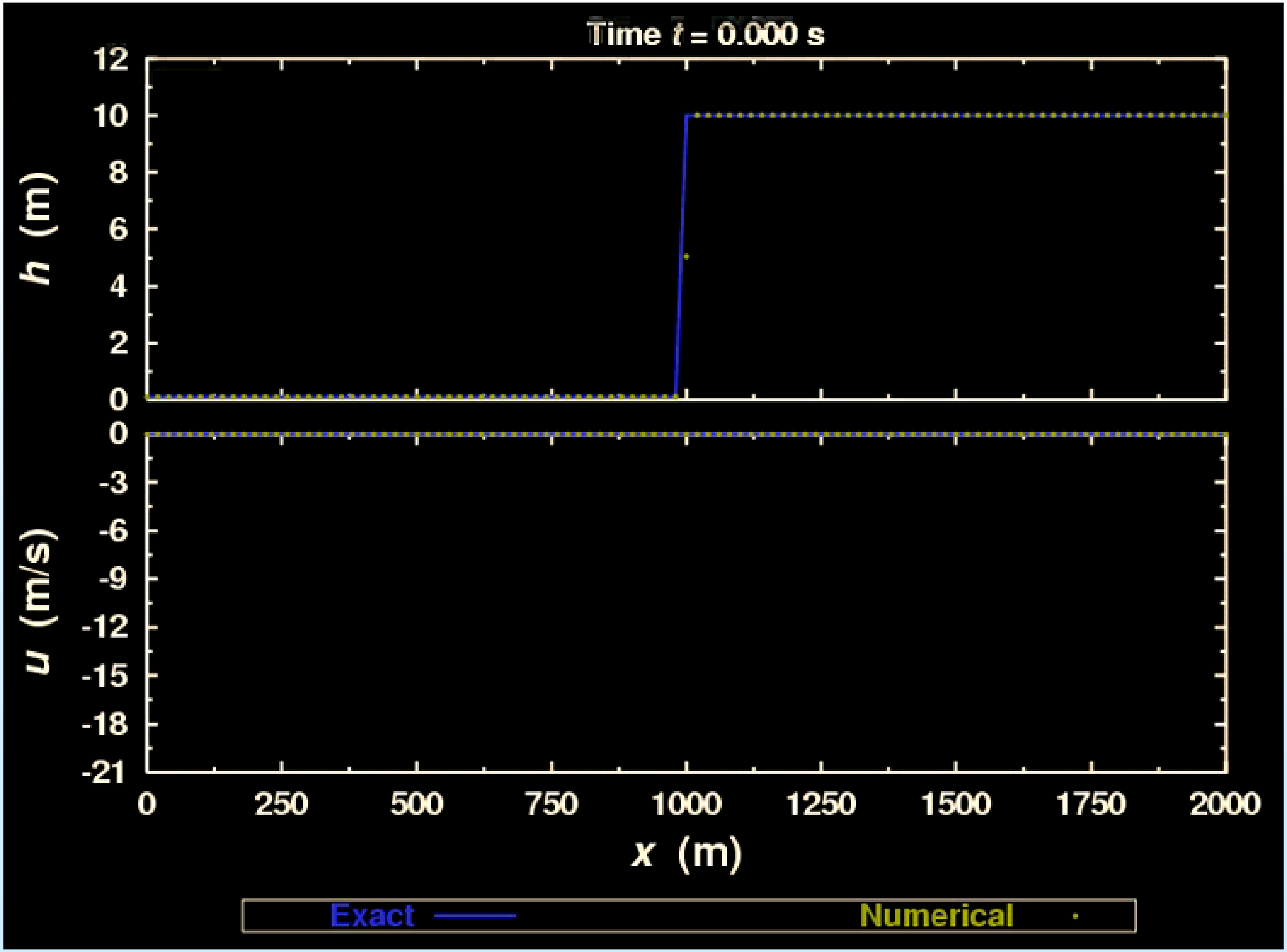
Dry Bed Problem



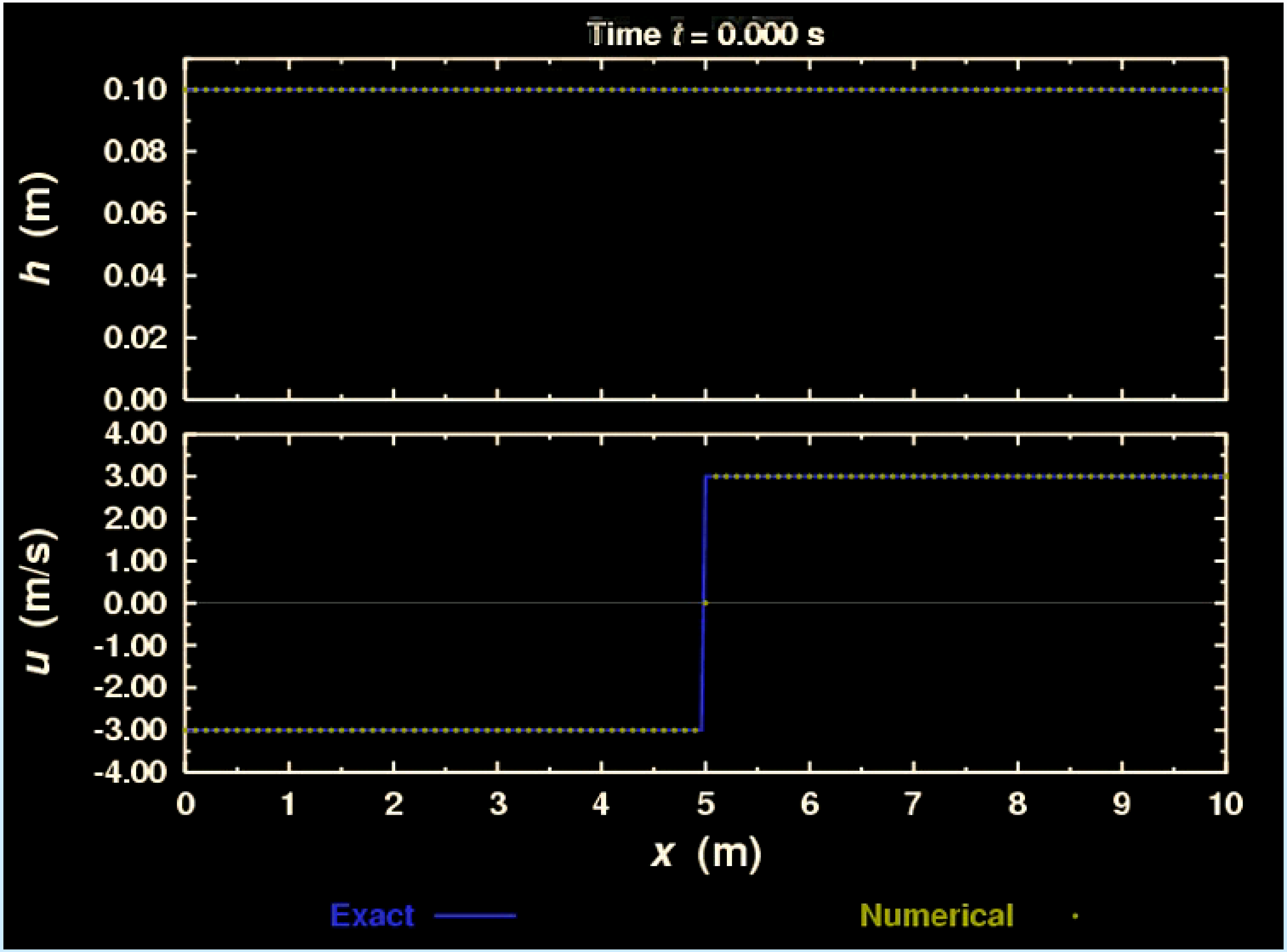
Wet Bed Problem



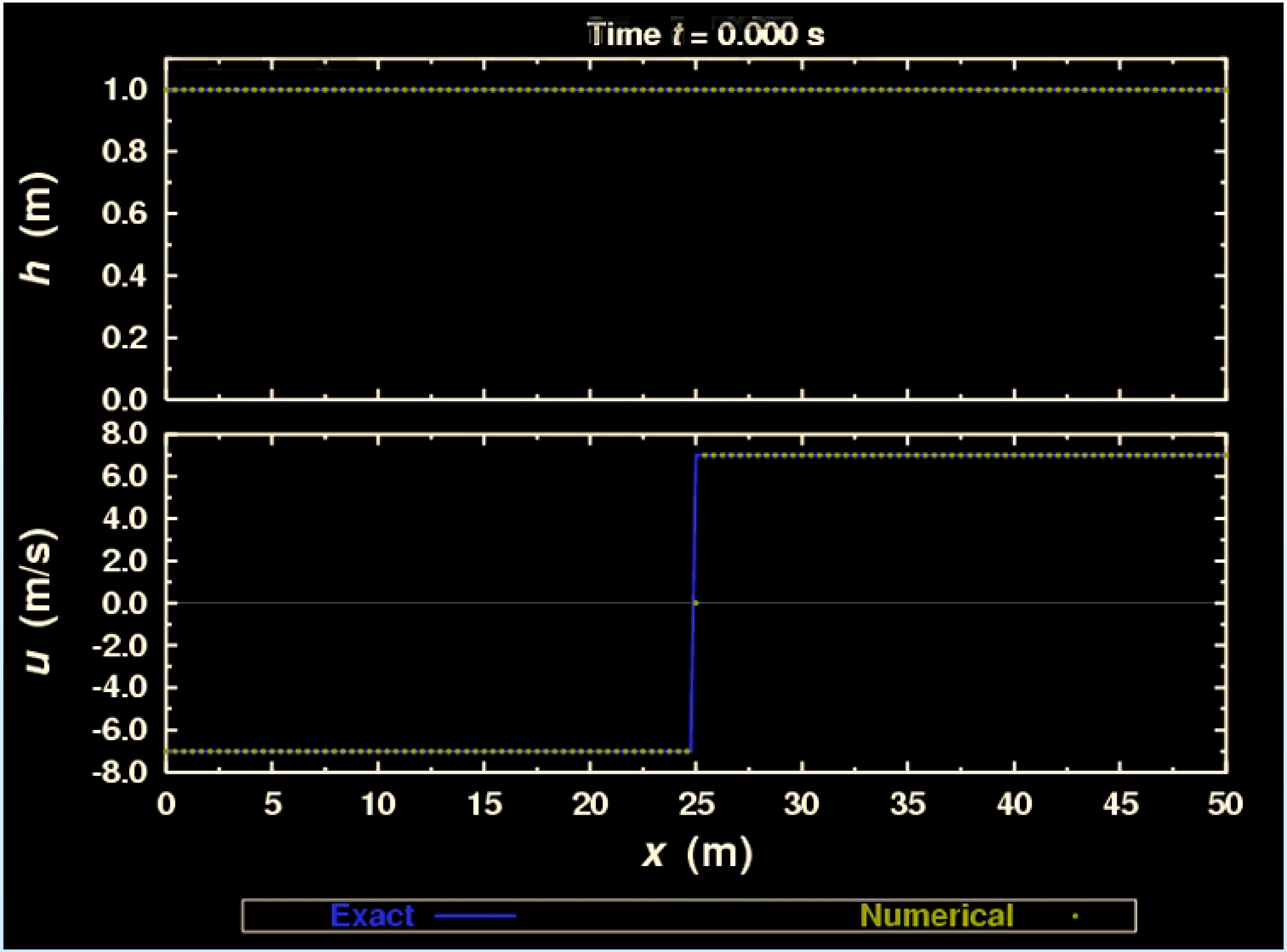
Wet Bed Problem



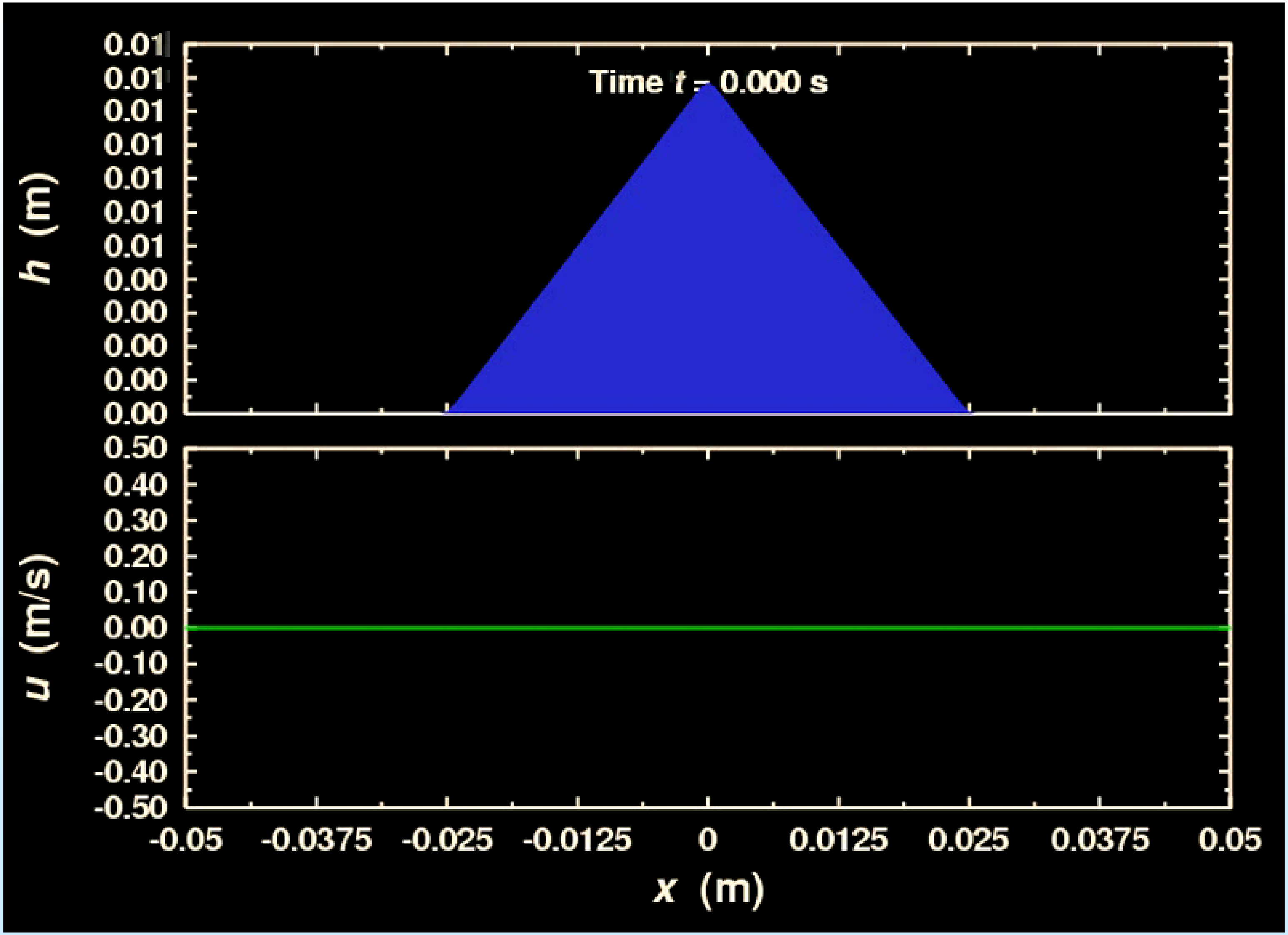
Red Sea Problem



Red Sea Problem

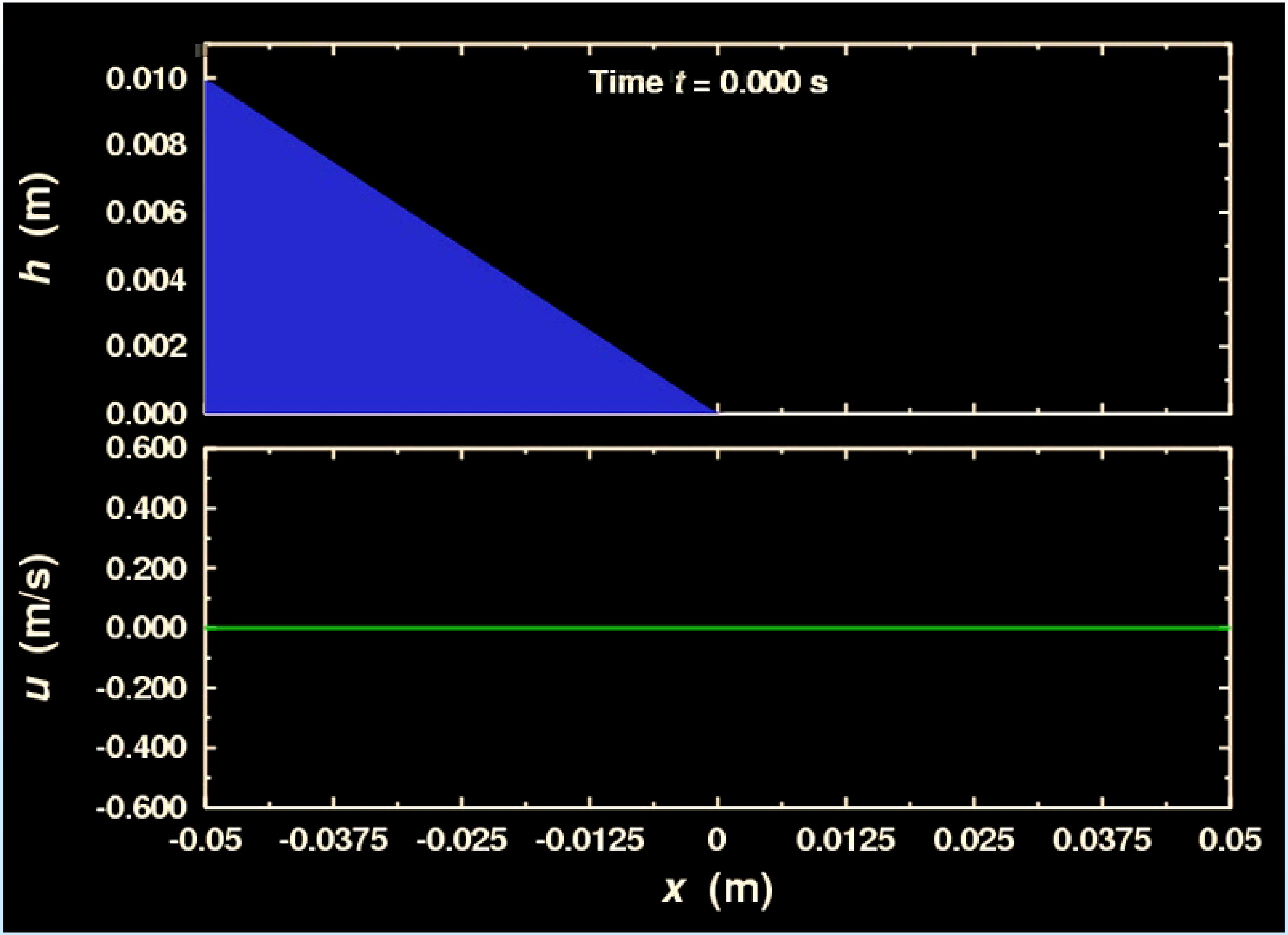


Spill



Time t = 0.000 s
h (m)
0.01
0.01
0.01
0.01
0.01
0.01
0.01
0.00
0.00
0.00
0.00
0.00
u (m/s)
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
-0.40
-0.50
-0.05 -0.0375 -0.025 -0.0125 0 0.0125 0.025 0.0375 0.05
x (m)

Wave Reflection



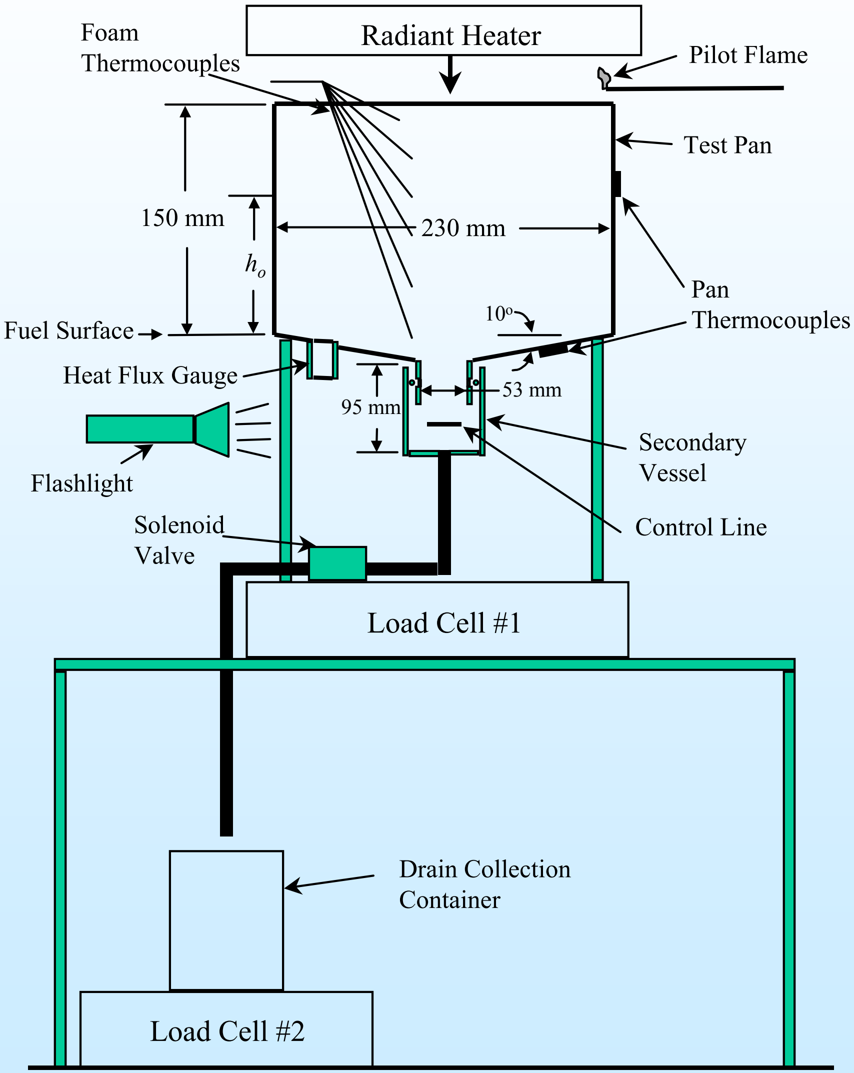
Next Steps in Modeling

- Adding in source terms
  - Frictional shear between the flow and the bed
  - Mass losses and gains
  - Validation
- 2-D solutions
  - Validation
- Foam flows

Experimental –Evaporation, Drainage, Suppression

- Static foam layer
  - Evaporation
  - Drainage
  - Time to fuel ignition
    - Suppression model
- Develop simple predictive methods
- Verify predictive methods

Test Apparatus



- Monitor mass
  - Drained
  - Foam
  - Calculate evaporated
- Radiant Heating
  - Up to 60 kW/m^2
- Temperature
  - Profile in foam
  - Pan
  - Drained solution
- Heat flux at fuel surface
- Tests with and without fuel
- Time to fuel ignition

Test Conditions

- Foam Height
  - 25, 50, and 75 mm
- Expansion Ratio
  - 3, 6, and 10
- Irradiance
  - 0, 20, 35, and 50 kW/m^2
- With and without fuel (JP-5)

Summary of Results

- Increasing irradiance
  - No affect on drainage rate
  - No affect on temperature distribution in foam
  - Decreases time to ignition
  - Increases evaporation rate
- Increasing foam height
  - No affect on evaporation rate
  - Affects drainage rate with time
  - Increases time to ignition
- Increasing expansion ratio
  - No affect on time to ignition
  - Slight affect on evaporation rate
  - Decreases drainage rate

Predicting Evaporation Rate

- Energy balance at foam surface
  - Foam preheated to 100°C
  - Ignore effects of bubble bursting, foam density at surface, transient heating
  - Foam is a gray surface

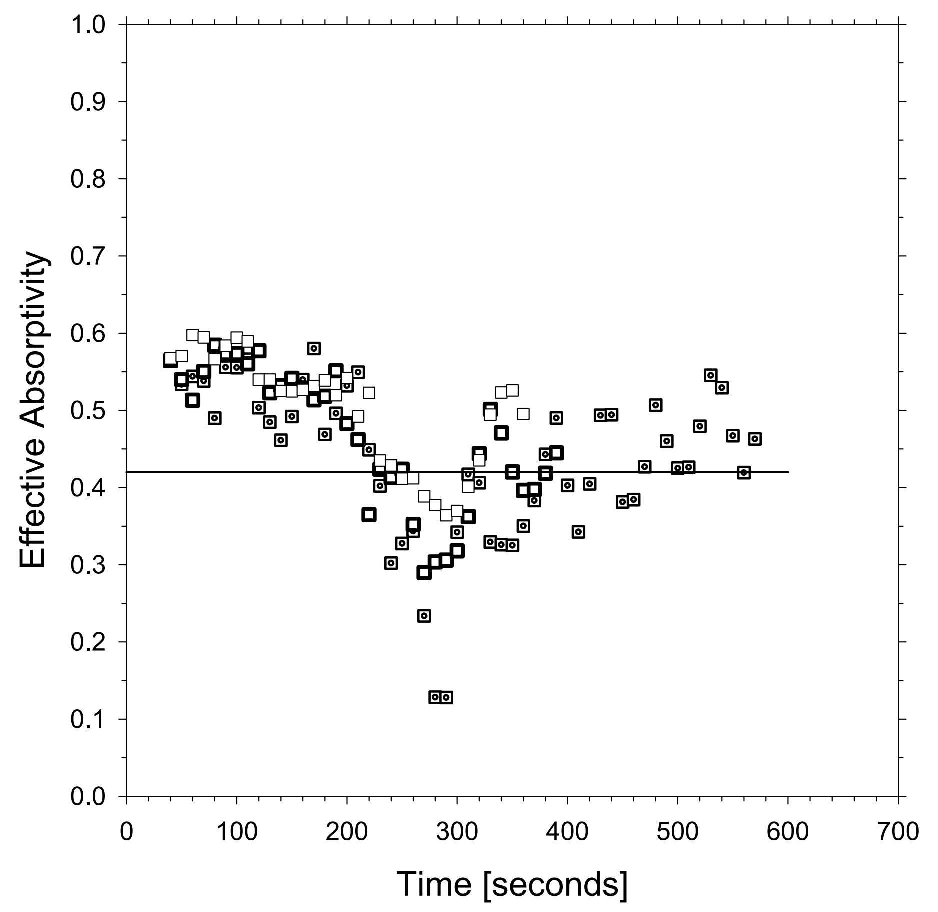
$$q''_{net} = \dot{m}''_{evap} \Delta h_v$$

$$\dot{m}''_{evap} \Delta h_v = \alpha_{foam} \frac{q''_{hfg}}{\varepsilon_{hfg}} + \alpha_{foam} \sigma T_{hfg}^4 - \varepsilon_{foam} \sigma T_s^4$$

$$\dot{m}''_{evap} = \left(\frac{\alpha_{foam}}{\varepsilon_{hfg}} \right) \left(\frac{q''_{hfg}}{\Delta h_v} \right)$$

$$\alpha_{foam} = 2{,}257 \frac{\dot{m}''_{evap}}{q''_{hfg,cl}}$$

Predicting Evaporation Rate

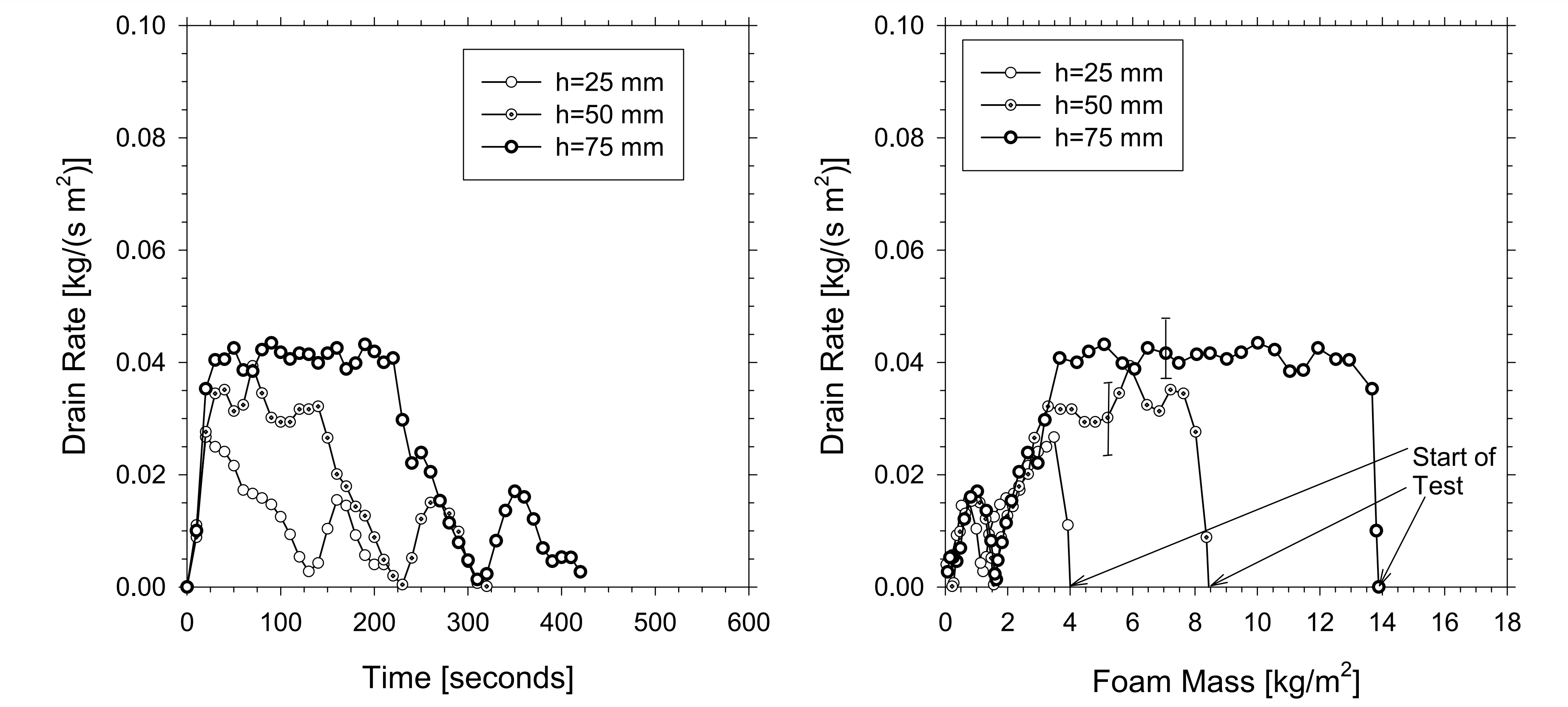


Expansion Ratio, *ER*	Effective Absorptivity, α_{foam}
3	0.34±0.09
6	0.42±0.06
10	0.41±0.04

Expansion Ratio = 6
Initial Height = 75 mm
Irradiance = 20, 35, 50 kW/m^2

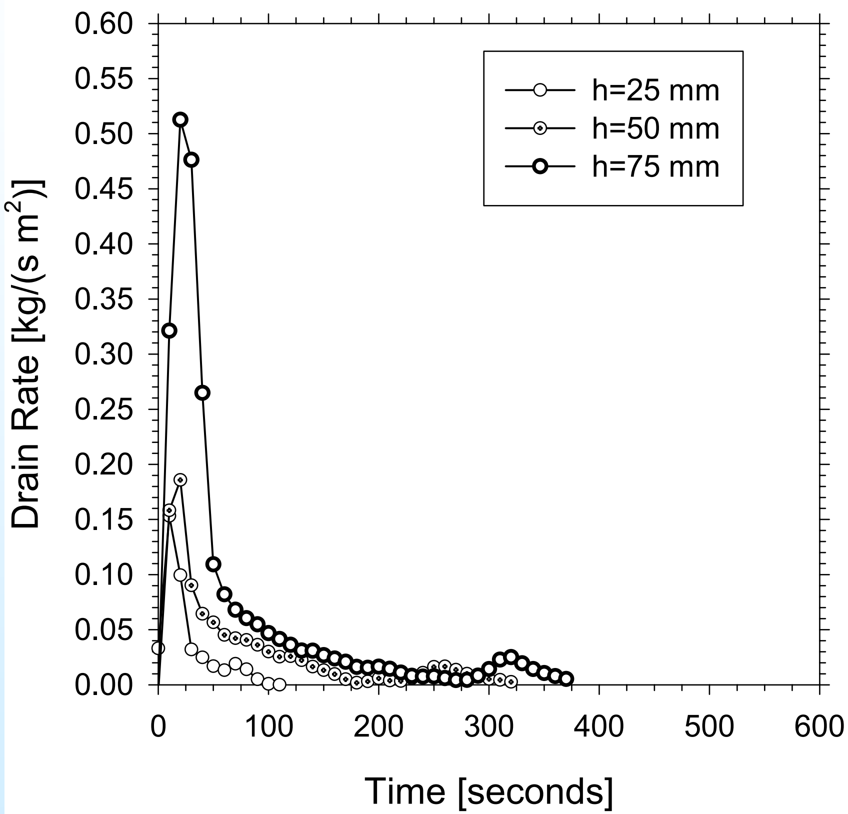
Predicting Mass Drained

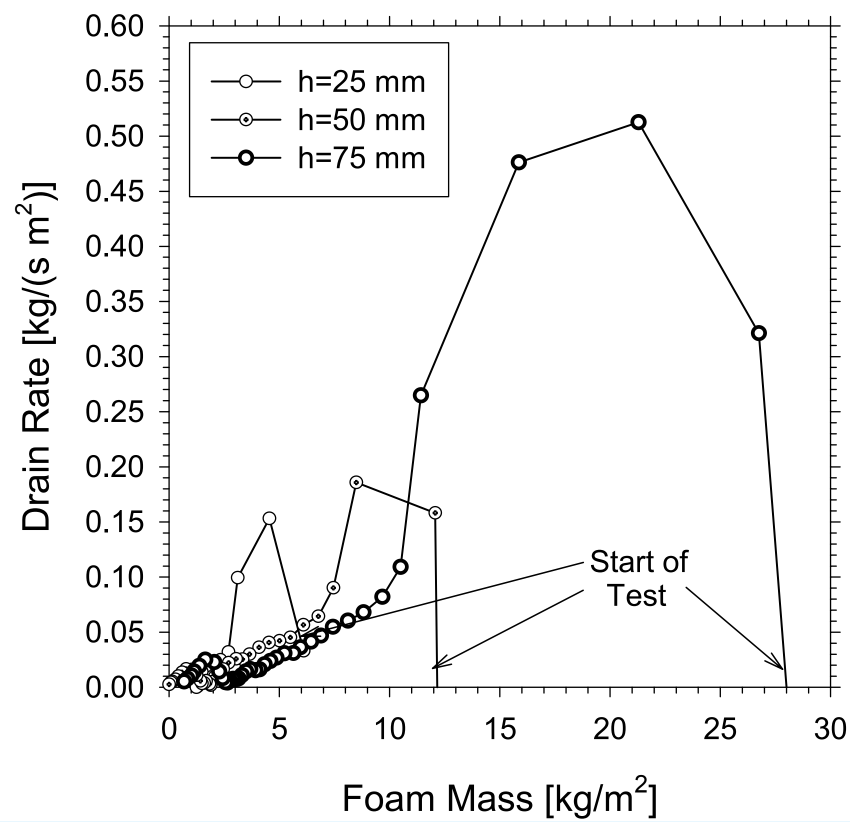
- Mass drained is related to foam mass on fuel



Expansion Ratio = 6 Initial Height = 25, 50, 75 mm Irradiance = 35 kW/m^2

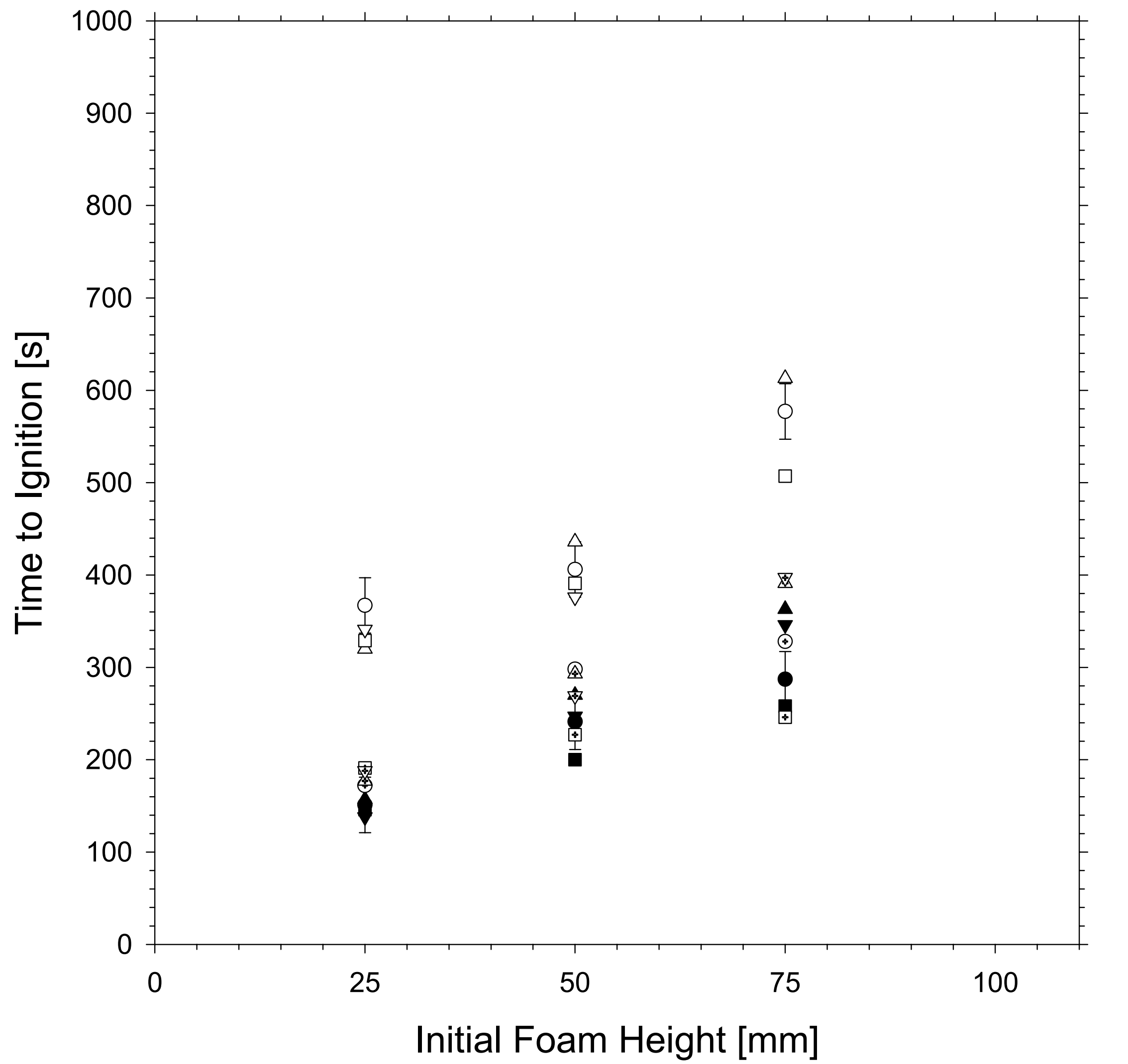
Predicting Mass Drained





Expansion Ratio = 3
Initial Height = 25, 50, 75 mm
Irradiance = 35 kW/m^2

Time to Ignition

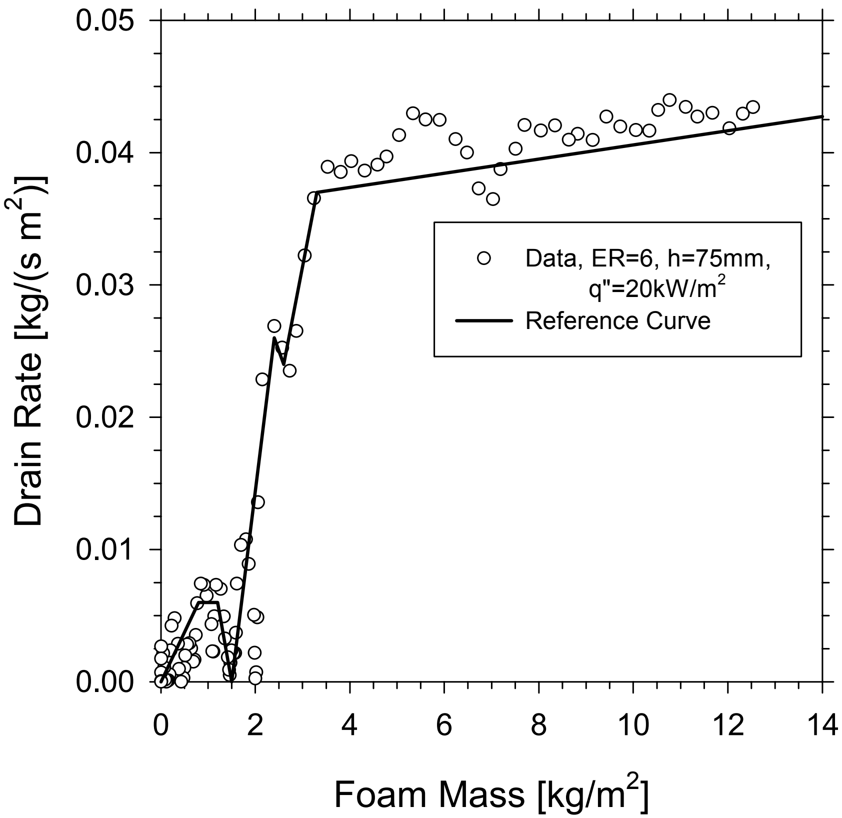


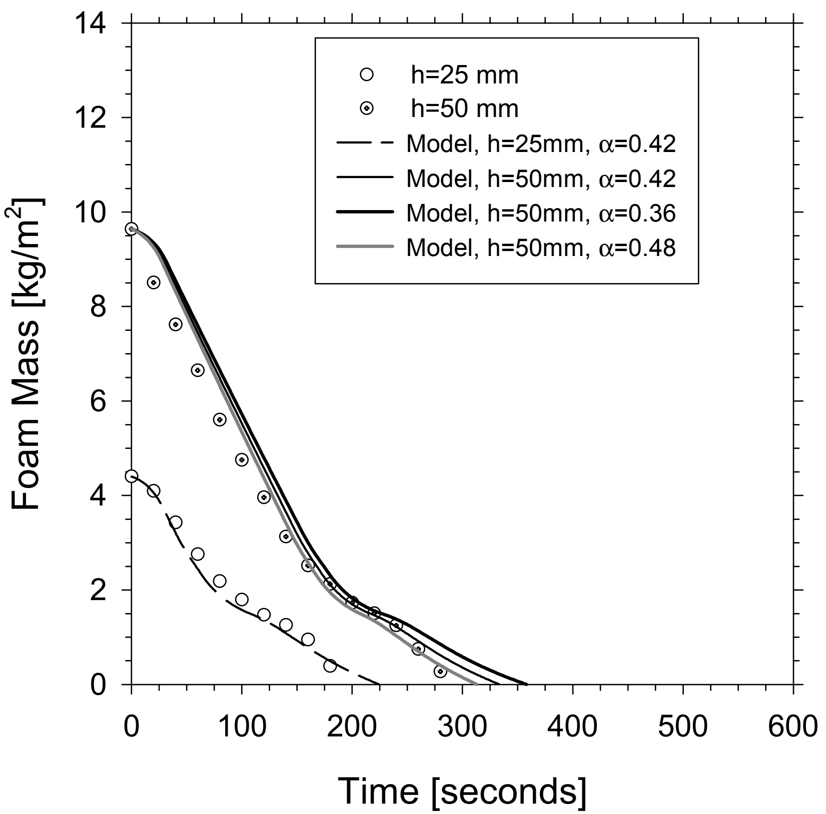
- Independent of expansion ratio
- Increases with
  - Decrease in irradiance
  - Increase in initial foam height
- Small amount of foam remaining at ignition in all cases
  - 0.86 kg/m^2 or 35 g
  - 75-97% of initial foam

Evaporation, Drainage and Suppression Models

- Evaporation
  - Effective absorptivity
- Drainage
  - Foam mass to predict drainage rate
    - Develop a reference curve
      - 75 mm thick foam layer
      - Moderate irradiance level (20 kW/m^2)
- Suppression
  - Critical foam mass
    - 0.90 kg/m^2

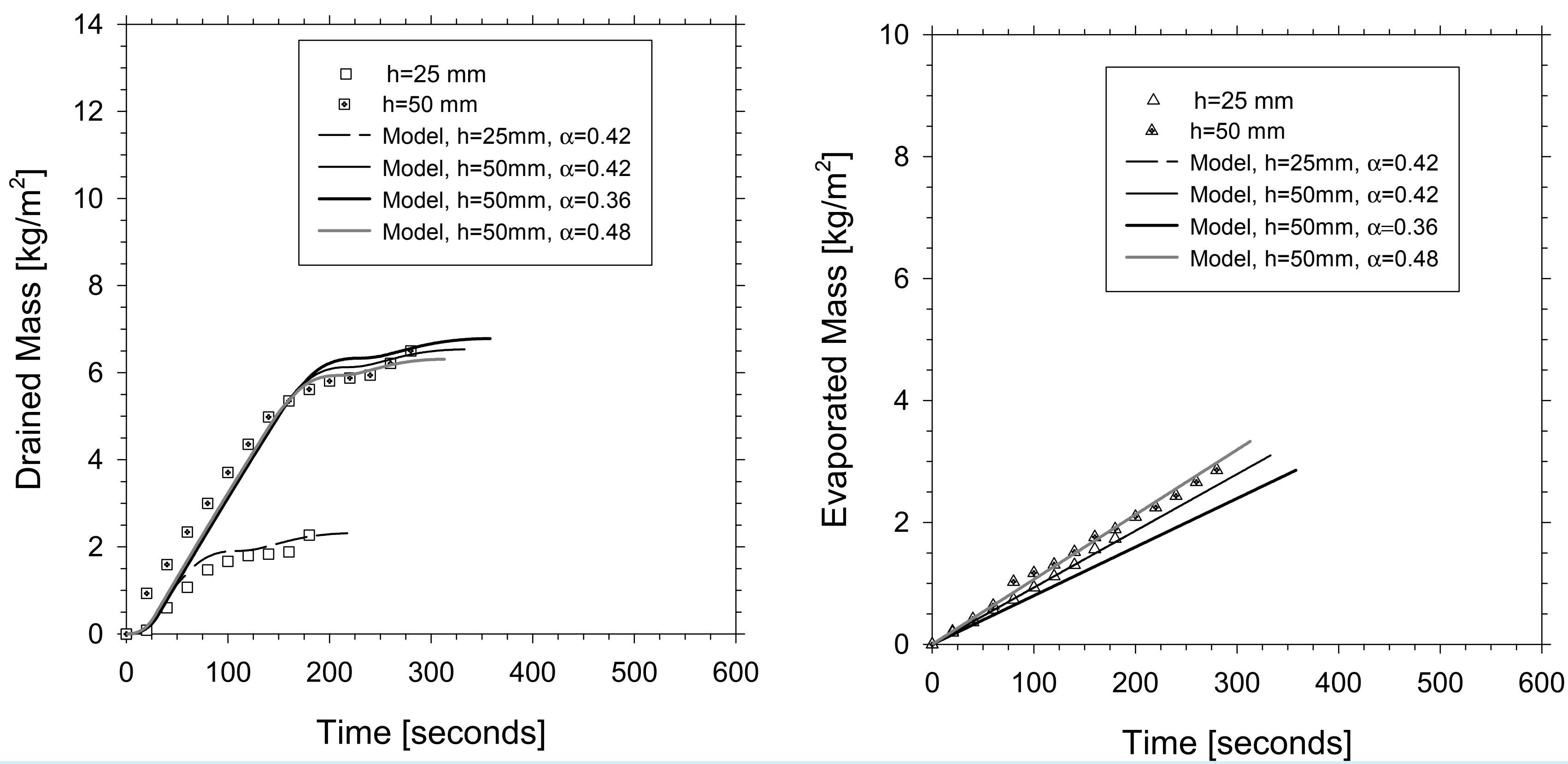
Validation of Drainage and Evaporation Models





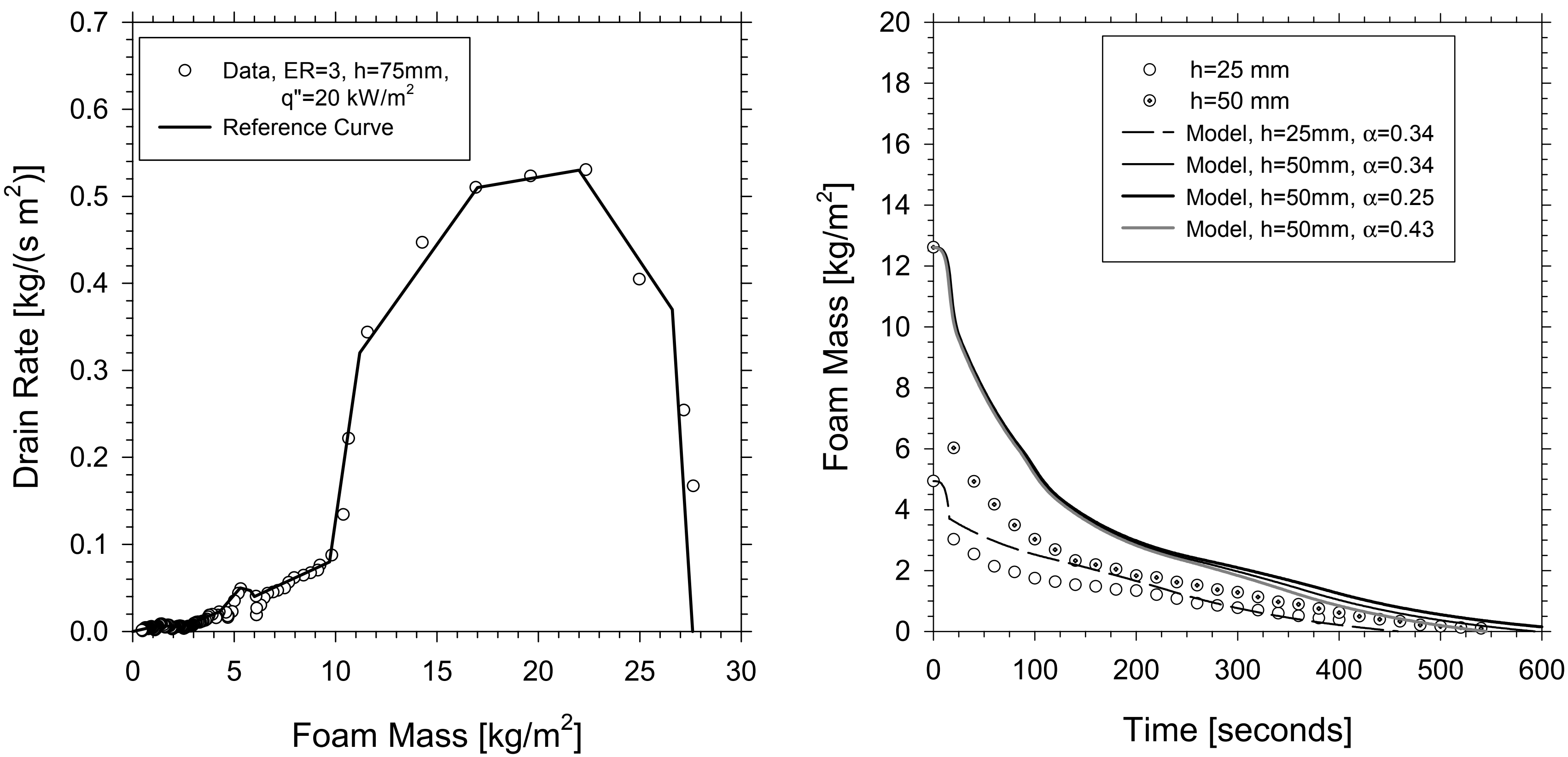
Expansion Ratio = 6
Initial Height = 25 and 50 mm
Irradiance = 50 kW/m^2

Validation of Drainage and Evaporation Models



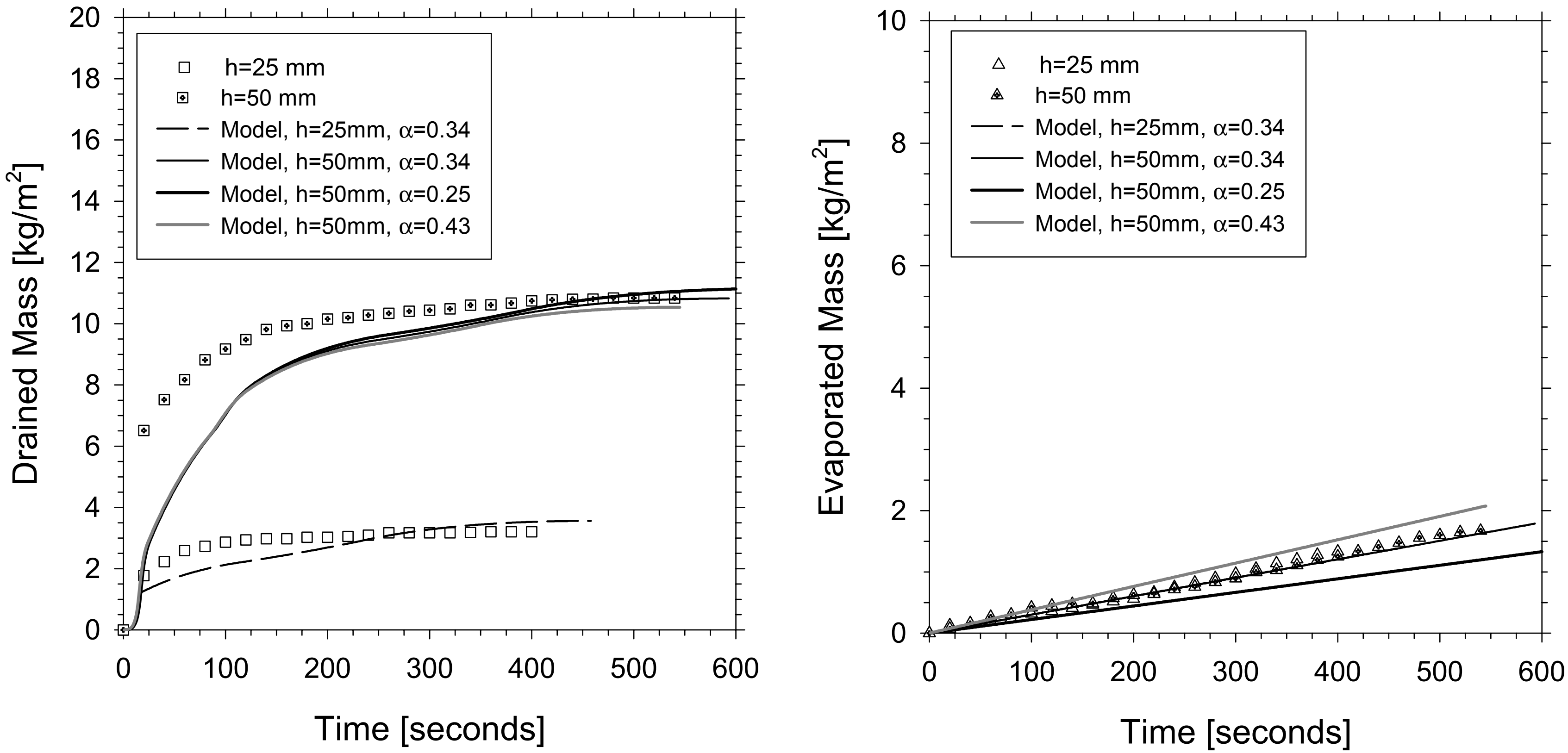
Expansion Ratio = 6
Initial Height = 25 and 50 mm
Irradiance = 50 kW/m^2

Validation of Drainage and Evaporation Models



Expansion Ratio = 3
Initial Height = 25 and 50 mm
Irradiance = 20 kW/m^2

Validation of Drainage and Evaporation Models



Expansion Ratio = 3
Initial Height = 25 and 50 mm
Irradiance = 20 kW/m^2

Next Steps in Experimental Work

- State equation for foam
  - Predict density
- Density profile
  - Potential sub-grid refinement of solution
- Effects of foam addition on drainage and evaporation rates
- Foam spreading parameters
  - Frictional shear between foam and fuel
  - Wind shear
  - Nozzle momentum
  - MIL-SPEC nozzle characterization

Accomplishments

- Solved and verified 1-D shallow water equations
- Developed and verified models for foam solution mass drained and evaporated
- Developed model for fuel ignition
- Developed theoretical models for some source terms
  - Frictional shear for non-newtonian fluids
  - Wind shear

Timeline for FY 03

TASK			Feb	Mar	April	May	June	July	Aug	Sept
1	Spreading Model									
	-1	Source Terms								
	-2	2-D								
	-3	Foam Flows								
2	Static Small-Scale Testing									
	-1	State Equation for Foam								
	-2	Density Profile								
	-3	Effects of Foam Addition (UMD)								
3	Foam Spread Testing									
	-1	Foam-Fuel Shear								
	-2	Wind Shear								
	-3	Nozzle Momentum (UMD)								
4	MIL-SPEC Nozzle Characterization (UMD)									
	-1	Density Distribution								
	-2	Velocity and Foam Drop Size								

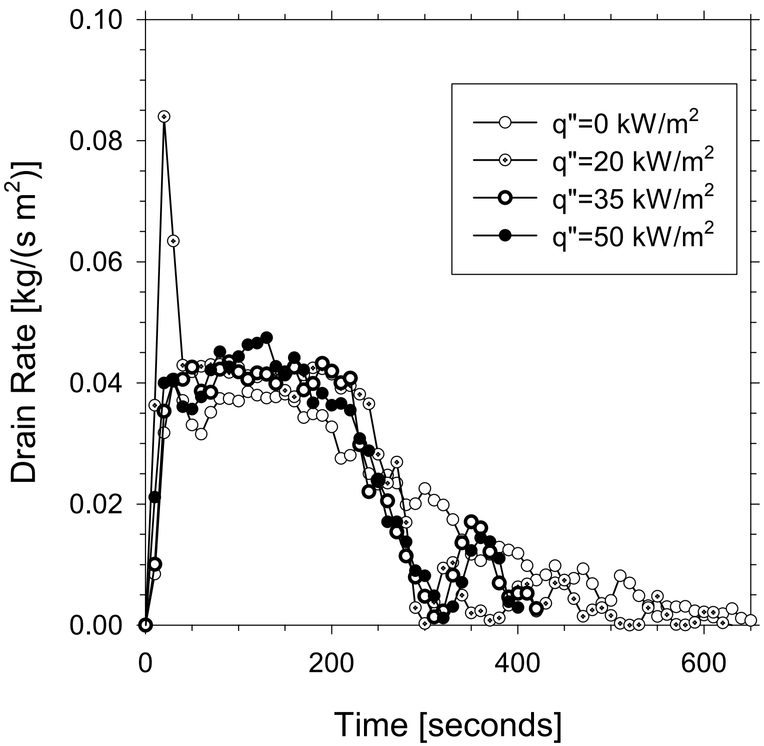
Timeline for FY04

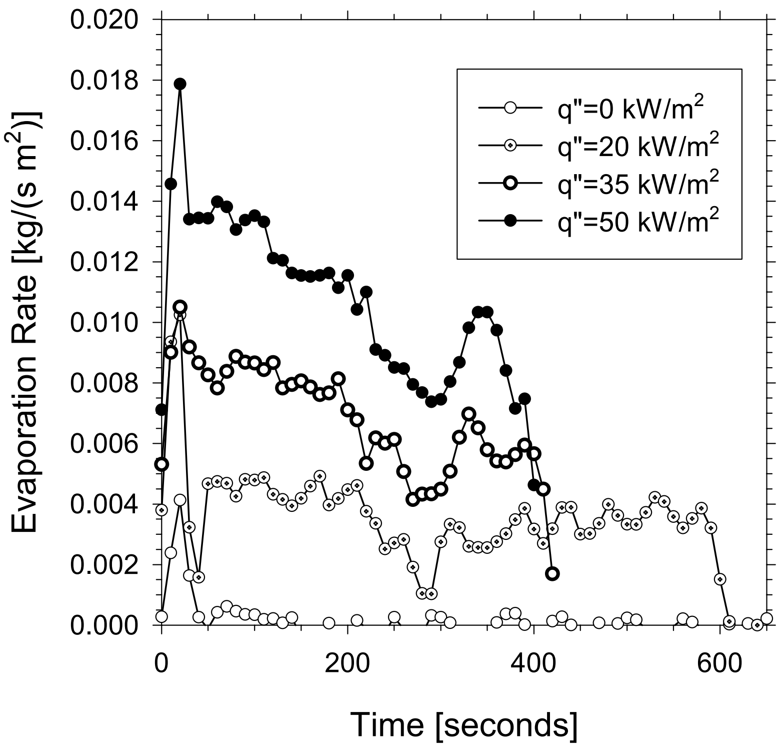
TASK			Oct	Nov	Dec	Jan	Feb	Mar	April	June	July	Aug	Sept
1	Spreading Model												
	-1	Foam Flows											
	-2	Validation with MIL SPEC Test											
	-3	Predictions of Larger Fires											
2	Static Small-Scale Testing												
	-1	Effects of Foam Addition (UMD)											
	-2	Data for AFFF using Nozzle											
3	Foam Spread Testing												
	-1	Data for AFFF using Nozzle											
4	MIL-SPEC Nozzle Characterization(UMD)												
	-1	Density Distribution											
	-2	Velocity and Foam Drop Size											
5	Other Nozzle Characterizations (UMD)												
	-1	Density Distribution											
	-2	Velocity and Foam Drop Size											
6	Large Scale Fire Suppression Testing (NRL)												
	-1	MIL SPEC 28 and 50 ft^2											
	-2	Larger Fire Tests											

Publications

- Journal Articles
  - Lattimer, Hanauska, Scheffey, and Williams, 2003, "The Use of Small-Scale Test Data to Characterize Some Aspects of Firefighting Foam for Suppression Modeling", *Fire Safety Journal*, in press.
- Conference Proceedings
  - Lattimer, 2003, "Modeling AFFF", *Proceedings of the Workshop on Fire Suppression Technologies*, February 25-26, Mobile, Alabama.

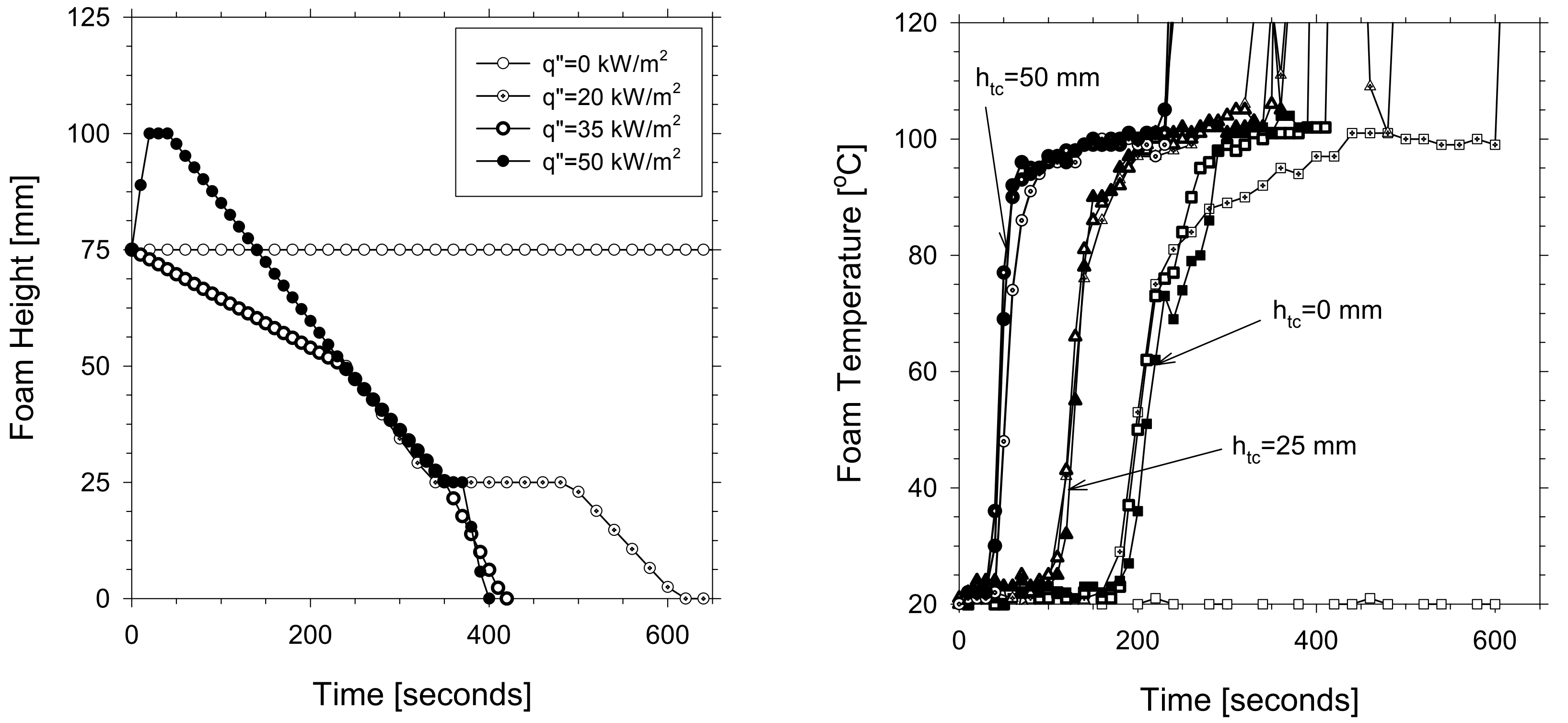
Drainage and Evaporation Rate





Expansion Ratio = 6
Initial Height = 75 mm
Irradiance = 0, 20, 35, 50 kW/m^2

Foam Height and Temperature



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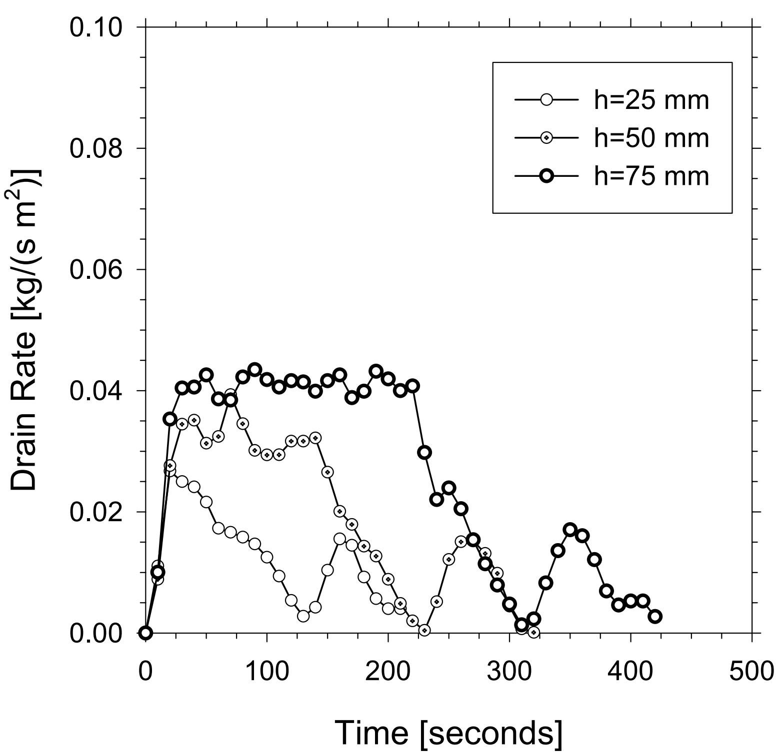
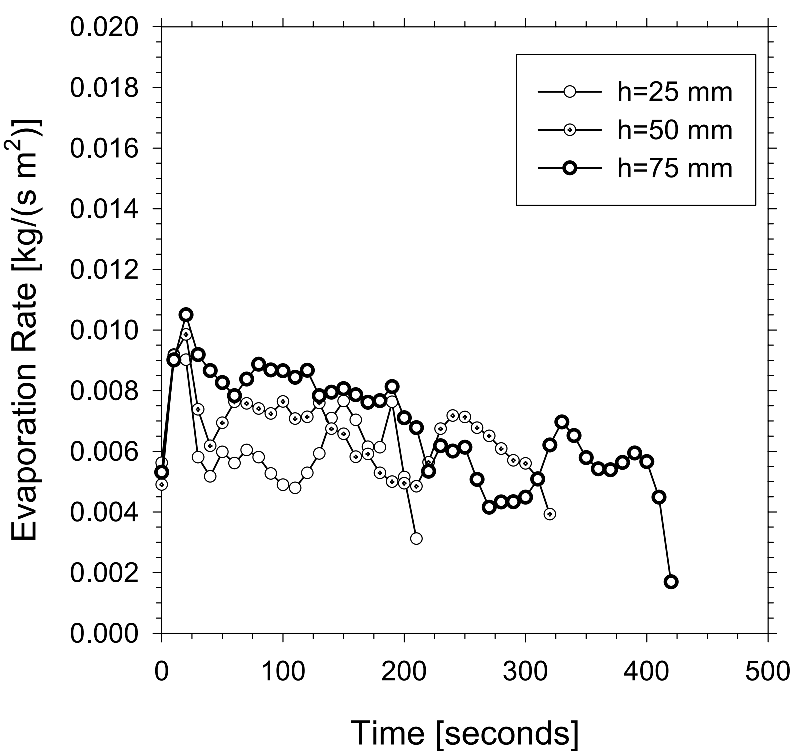
Drainage and Evaporation Rate





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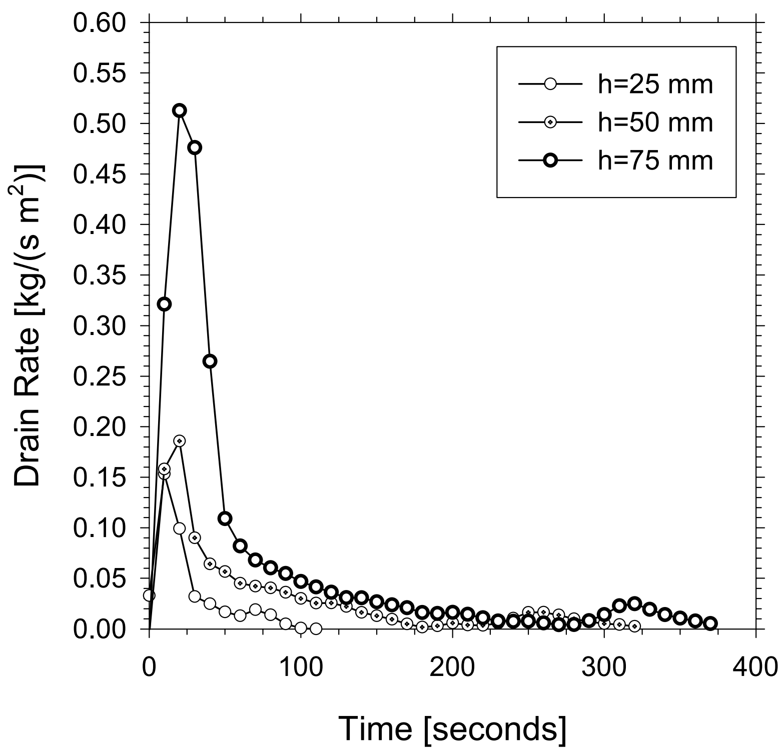
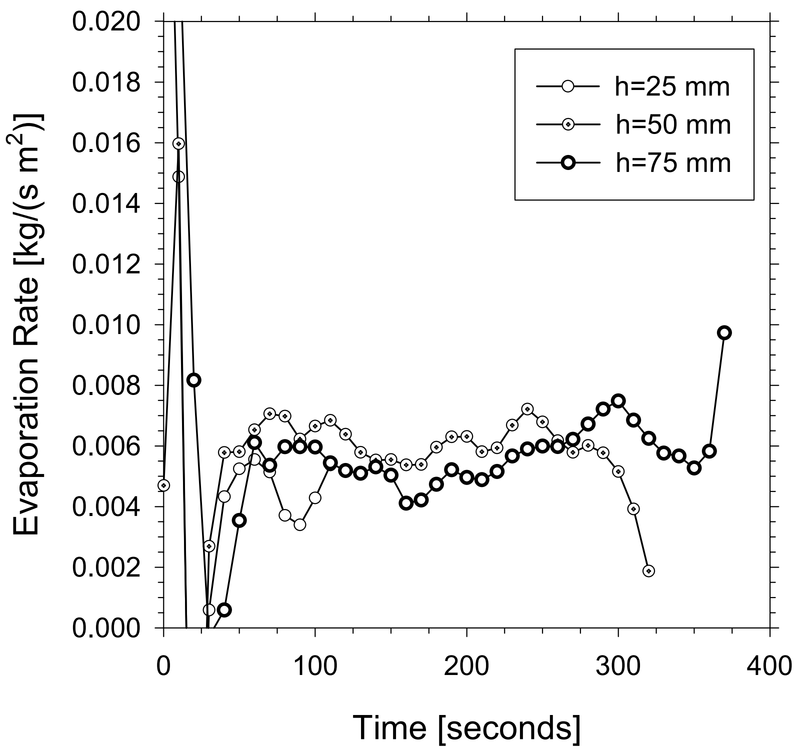
Initial Height = 25, 50, 75 mm
Irradiance = 35 kW/m^2

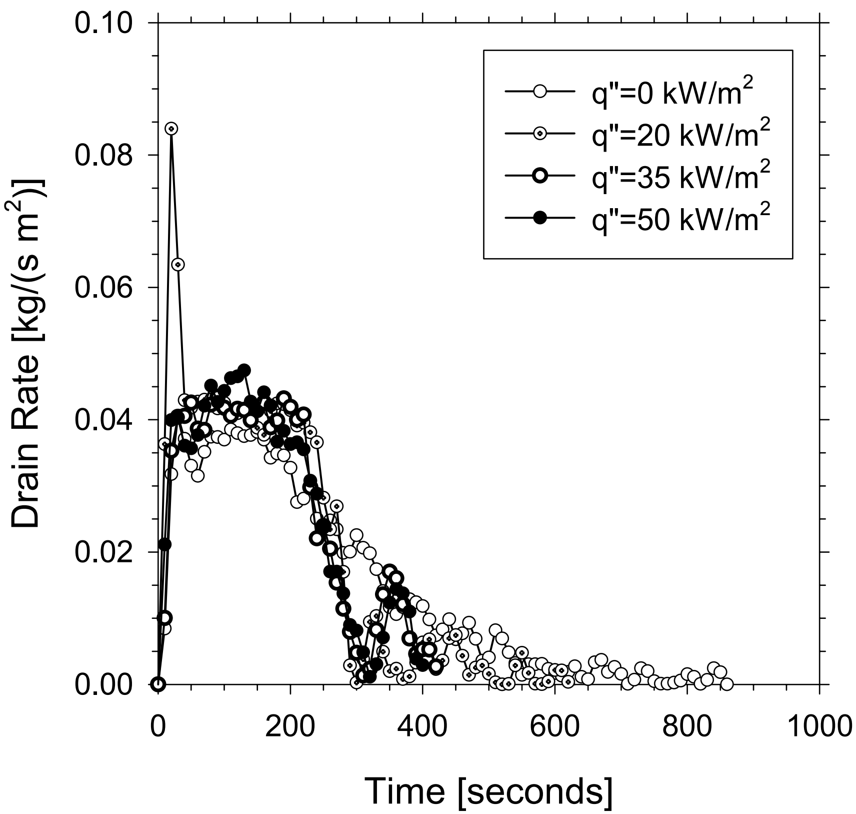
Drainage and Evaporation Rate

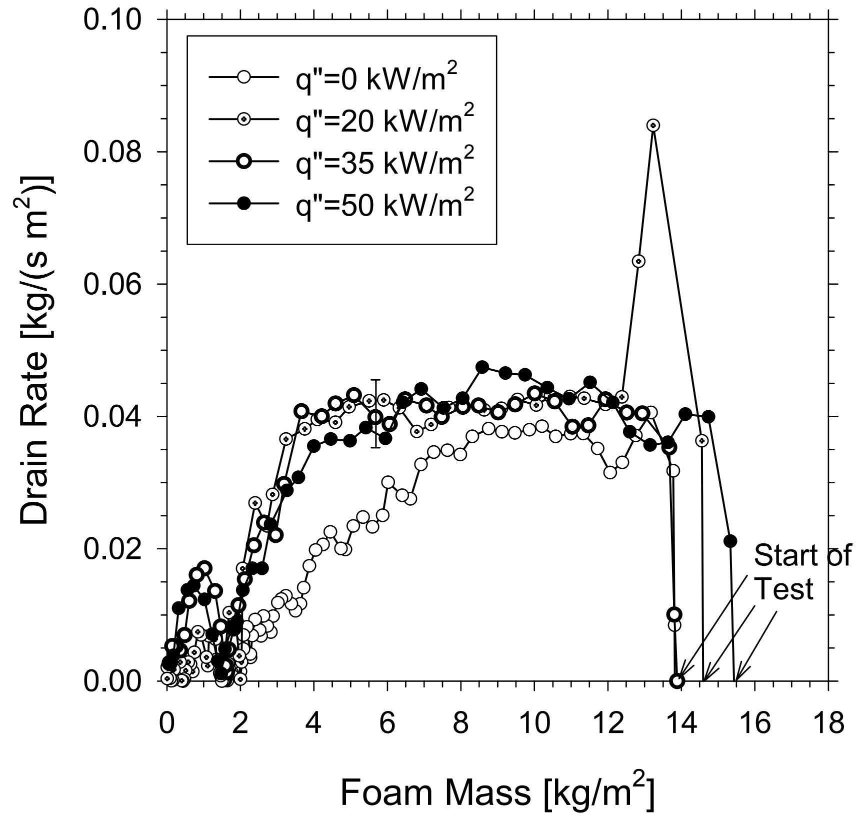




Expansion Ratio = 3
Initial Height = 25, 50, 75 mm
Irradiance = 35 kW/m^2

Predicting Mass Drained





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Initial Height = 75 mm
Irradiance = 0, 20, 35, 50 kW/m²